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BACKWARD COLLINEAR GUIDED-WAVE-ACOUSTO-OPTIC INTERACTIONS IN SINGLE MODE FIBERS

by

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ABSTRACT

Theoretical studies of backward collinear guided-wave-acousto-optic (BCGWAO) interactions in single mode fibers are described. Both single mode optical and acoustic waves are guided in the fiber core simultaneously of a cladded fiber. At very high acoustic frequency (>10 GHz) acoustic wavenumber of guided acoustic modes can be twice of the optical wavenumber of the guided optical modes. Thus the incident single optical HE_{11} mode propagating in the forward direction is coupled to that in the backward direction due to the index grating induced by the guided acoustic mode. The high efficiency is achieved due to the perfect matching of electromagnetic fields for the forward and backward propagating optical waves and a long interaction length along the fiber. The coupling coefficient and wavelength selectivity of BCGWAO interaction in a single mode optical fiber using guide longitudinal types of acoustic waves are given. Practical considerations are also discussed.

1. INTRODUCTION

In-line fiber-optic signal processing devices which process guided light directly within the optical fiber may eliminate the need for the off-line planar integrated optical and electronic devices in a fiber-optic communication path. They can be simple, inexpensive and small size. Acousto-optic interactions performed directly with the guided optical waves in optical fibers have been demonstrated using symmetric standing bulk acoustic waves [1,2], propagating bulk [3-6], surface [3] and flexural [7] acoustic waves as well as thermal excited phonons (Stimulated Brillouin phenomenon) [8,9]. Fiber-optic phase modulators [1,2], frequency shifters [3-7], amplitude modulators, switches and filters [10] may be achieved by these devices and potentially used in the fiber optic telecommunication and sensor field.

In above mentioned previous works a research group in Stanford university applied the collinear guided wave acousto-optic (CGWAO) interaction to achieve fiber optic frequency shift function [7]. Guided acoustic flexural waves at 8 MHz has been used to convert one guided optical mode to another in a two-mode optical fiber. These two optical modes propagate in the same 'forward' direction. At such low frequency the acoustic wavelength is much larger than the core diameter of the optical fiber, the energy of the guided acoustic waves is not concentrated in the fiber core. In this work a special fiber (two-mode) was required.

Brillouin scattering phenomena in single mode optical fibers have been also reported, but only a few involving backward

Brillouin scattering (BBS) are cited here [8-11]. BBS is also an acousto-optic phenomenon, but acoustic waves are generated by the heat induced by the guided light inside the fiber core rather than the ultrasonic transducers. For BBS a nearly infinite number of acoustic modes exist and many are responsible for the light scattering [11,12], thus it is difficult to select the frequency of the guided acoustic waves. Long length of fiber is also required to achieve the required efficiency.

In this paper a theoretical analysis for backward collinear guided-wave-acousto-optic (BCGWAO) interactions inside the fiber core of a single mode fiber is described. This interaction is believed to be responsible for the experimental observation of BBS reported in Ref.[9,11]. Furthermore, the high frequency ultrasonic transducers (> 10 GHz) have been demonstrated recently [13,14]. It means that the high frequency acoustic waves for the BCGWAO interaction inside a single mode cladded fiber may be excited directly by an ultrasonic transducer. Figure 1 shows a considered geometry with the ultrasonic transducer attached to the fiber end. The BCGWAO interaction takes place by converting the single guided optical mode (LP_{01} or HE_{11}) propagating in the forward (say +z) direction to the same optical mode but propagating in the backward (-z) direction due to the high frequency travelling acoustic waves in the backward (-z) direction with k_a equal to $2k_o$, where k_a and k_o are the acoustic and optical wavenumbers respectively. Under such condition the diameter of the fiber core is about a few or tens acoustic wavelengths. A cladded fiber may be also designed to be able to

guide both optical and acoustic waves in single mode operation inside the fiber core [15] and the requirement of such fiber is the key difference between the present work and the work performed in Ref.[7]. Practical considerations especially for the geometry shown in Fig.1 will be discussed.

2. ANALYSIS FOR THE BCGWAO INTERACTION

In the analysis for BCGWAO interaction, fibers are assumed to satisfy the weakly guiding conditions for both optical [16,17] and acoustic waves [18,19]. It means that the phase velocity in the fiber core is slightly smaller than that in the fiber cladding. The geometry considered in the present study is given in Fig.1. An ultrasonic transducer is attached to the termination of a cladded fiber in which both single mode optical and acoustic waves propagate inside the fiber core. The electrodes of this transducer can be either transparent or reflective. The acoustic waves are launched into the fiber through the ultrasonic transducer which determines the desired propagating acoustic mode. This is the difference between the proposed method and the BBS reported in Ref.[10]. The guided optical waves are launched from a light source.

When guided acoustic waves propagate inside the fiber core, they produce a periodic modulation of the optical refractive index via the elasto-optical effect. This provides a spatial grating for the guided optical waves. The possible collinear guided wave acousto-optic interactions are illustrated in Figs. 2(a)-(c). These interactions must obey the conservation of wave-vector

(momentum) and frequency (energy) as described as equations (1) and (2) respectively

$$k_{oi} + k_{a} = k_{od} \tag{1}$$

$$\Omega_{oi} \pm f_{a} = \Omega_{od} \tag{2}$$

The interaction will switch the energy from one guide optical mode (wavenumber k_{oi}, frequency Ω_{oi}) to another (wavenumber k_{od}, frequency Ω_{od}) due to one guided acoustic mode (wavenumber k_{a}, frequency f_{a}). For the CGWAO interactions shown in Figs.2(a) and 2(b) a birefringent or two mode optical fibers are required. Here, only single mode (LP_{01}) optical fibers are considered, therefore BCGWAO interation shown in Fig.2(c) is taken place and the frequency shift is downward (-ve sign in Eqn.2).

3.1 Dispersion Equations for Single Mode Operation

Under weak guidance conditions the dispersion equation for the single optical mode (LP_{01}) [15,16], single shear (F_{11}) [18] and longitudinal (L_{01}) [19] acoustic mode can be approximated expressed in an identical mathematical form as follows [18-20]

$$\frac{J_0(U)}{U J_1(U)} - \frac{K_0(W)}{W K_1(W)} = 0 \tag{3}$$

where J and K are Bessel and modified Bessel functions respectively, and

$$U = \omega a \left(\frac{1}{v_1^2} - \frac{1}{v^2}\right)^{1/2} \tag{4}$$

$$W = \omega a\left(\frac{1}{v_2^2} - \frac{1}{v^2}\right)^{1/2} \qquad (5)$$

$$V = \omega a\left(\frac{1}{v_1^2} - \frac{1}{v^2}\right)^{1/2} \qquad (6)$$

where a is the core radius; v_1 and v_2 are the phase velocity of the core and cladding materials respectively. For opitcal LP_{01} mode $v_1 = C/n_1$ and $v_2 = C/n_2$, where n is the refractive index. For acoustic F_{11} mode, $v_1 = v_{S1}$ and $v_2 = v_{S2}$ and for L_{01} mode $v_1 = v_{L1}$ and $v_2 = v_{L2}$. a is the core radius of the cladded fiber. $= 2f$ where f is the frequency.

V is a normalized frequency which has no dimension [16,17,15]. If V is less than 2.405 the fiber is operated in the single mode regime. The dispersion curves for a few lower order modes are given in Fig.3. It is interesting to note that when V is close to but smaller than 2.405 the dispersion equation (3) can be further approximated as [16]

$$U(V) = 2.405\, e^{-1/V} \qquad (7)$$

Field distributions of these modes can be found in Refs.[16-19].

3.2 BCGWAO Interaction

Since only longitudinal waves were observed by the high frequency ultrasonic transducers [13,14], thus in the paper the longitudinal L_{01} mode but not the shear F_{11} mode is selected for the analysis. If the ultrasonic transducer in Fig.1 is a

longitudinal type, then L_{01} acoustic mode may be efficiently excited.

3.2a Selection of Fiber Parameters

Since the acoustic frequency required for the BCGWAO interaction is very high, the dopants such as GeO_2 in doped fused silca act like inhomogeneities and induce higher acoustic loss. In order to reduce such a loss pure fused silica is preferrable as the core material and thus it is used here for the calculation. The assumed core radius and the operating optical wavelength of the single mode optical fiber is 3 and 1.31 μm respectively [21]. Equation (6) can be rewritten as

$$V_o = ka\delta_o = k_o a [1-(n_2/n_1)^2]^{1/2} \quad (8)$$

for the guided optical waves;

$$V_a = ka\delta_a = k_a a [1-(v_{L2}/v_{L1})^2]^{1/2} \quad (9)$$

for the guided longitudinal acoustic waves.

At 1.31 um optical wavelength, n_1 of the pure fused silica is equal to 1.4465 extrapolated from the data in Ref.[22]. Let V_o for the guided LP_{01} mode be 2.405. From Eqn.(8) we obtain n_2 = 1.4367. The density (ϱ), longitudinal (v_L) and shear wave velocity (v_S) for fused silica is 2202 kg/m^3, 5933 m/s and 3764 m/s respectively [20]. In order to meet the criterion $k_a = 2k_o$ for longitudinal acoustic waves, from Eqns.(8)&(9) V_{L2} is then equal to 1.0068 V_{L1}.

3.2b Coupling Coefficients

Diffraction of guided optical waves due to guided acoustic waves is described by the coupling equation [23]

$$\frac{dA_i(z)}{dz} = -j\, C^{*}(z)\, A_d(z)\, e^{-j2\delta z} \tag{10a}$$

$$-\frac{dA_d(z)}{dz} = -j\, C^{*}(z)\, A_i(z)\, e^{j2\delta z} \tag{10b}$$

where A_i and A_d are the amplitudes of incident and diffracted optical waves, respectively; 2δ is the shift from the Bragg condition given by Eq.(1) and is written as

$$2\delta = -k_{od} - k_{oi} + k_a . \tag{11}$$

The coupling coefficient C(z) is generally a function of distance z along the longitudinal axis of the fiber. The superscript * denotes the complex conjugate. In this study the acoustic wave propagation loss in the BCGWAO interaction region is assumed to be negligible, thus C(z) is independent of z. Then, for initial conditions of $A_i(0)=1$ and $A_d(L)=0$ and L being the interaction length, Equation (10) has a solution as

$$A_i(L) = e^{-j\delta L}\, \frac{\sqrt{|C|^2 - \delta^2}}{\sqrt{|C|^2 - \delta^2}\cosh\{\sqrt{|C|^2 - \delta^2}\, L\} - j\delta \sinh\{\sqrt{|C|^2 - \delta^2}\, L\}} \tag{12a}$$

$$A_d(0) = \frac{-jC \sinh\{\sqrt{|C|^2 - \delta^2}\, L\}}{\sqrt{|C|^2 - \delta^2}\cosh\{\sqrt{|C|^2 - \delta^2}\, L\} - j\delta \sinh\{\sqrt{|C|^2 - \delta^2}\, L\}} \tag{12b}$$

A coupling efficiency η is derived from Eq.(12) as

$$\eta = \frac{|A_d(0)|^2}{|A_i(L)|^2} = \left[1 + \frac{1 - \delta^2/|C|^2}{\sinh^2\left\{\sqrt{|C|^2 - \delta^2}\, L\right\}} \right]^{-1} \tag{13}$$

and is simplified under the condition of $\delta = 0$ as

$$\eta_0 = \tanh^2(|C|L) \tag{14}$$

The coupling coefficient C is represented by a summation

$$C = C^t + C^z + C^{rz} \tag{15}$$

where C^t and C^z are the coupling coefficients for optical transverse and longitudinal components, respectively, and are given by

$$C^t = \frac{\omega_o \varepsilon_0}{4} \left(\iint E_r^* \, \Delta\varepsilon_{rr} \, E_r + E_\phi^* \, \Delta\varepsilon_{\phi\phi} \, E_\phi \right) r dr d\phi \tag{16a}$$

$$C^z = \frac{\omega_o \varepsilon_0}{4} \iint E_z^* \, \Delta\varepsilon_{zz} \, E_z \, r dr d\phi \tag{16b}$$

where ω_o is the optical angular frequency and ε_0 is the dielectric constant of free space. The diagonal components of dielectric purterbations $\Delta\varepsilon_{rr}$, $\Delta\varepsilon_{\phi\phi}$ and $\Delta\varepsilon_{zz}$ are induced by acoustic strains S_{ij} through photoelastic constants p_{ij} as

$$\Delta\varepsilon_{rr} = -n^4(r)[p_{11}(r) S_{rr} + p_{12}(r) S_{\phi\phi} + p_{12}(r) S_{zz}] \tag{17a}$$

$$\Delta\varepsilon_{\phi\phi} = -n^4(r)[p_{12}(r) S_{rr} + p_{11}(r) S_{\phi\phi} + p_{12}(r) S_{zz}] \tag{17b}$$

$$\Delta\varepsilon_{zz} = -n^4(r)[p_{12}(r)\,S_{rr} + p_{12}(r)\,S_{\phi\phi} + p_{11}(r)\,S_{zz}] \qquad (17c)$$

In addition to these three diagonal components, there exists a non-zero off-diagonal component

$$\Delta\varepsilon_{rz} = -2n^4(r)p_{44}(r)\,S_{rz} \qquad (18)$$

which induces the coupling coefficient C^{rz} between optical transverse and longitudinal components as given by

$$C^{rz} = \frac{\omega_o\varepsilon_0}{4}\iint E_z^{*}\,\Delta\varepsilon_{rz}\,E_r\,rdrd\phi \qquad (19)$$

However, since the longitudinal component E_z of optical fields in fibers is small in addition to the fact that S_{rz} is small in L_{01} acoustic mode, as shown later, this coupling component can be neglected. Therefore, the coupling coefficient C is approximated by

$$C = C^{t} + C^{z} \qquad (20)$$

We restrict discussions on the interaction between optical HE_{11} mode and acoustic longitudinal L_{01} mode. Under the weakly guiding conditions, acoustic strains for the L_{01} mode are written as [19]

$$S_{rr} = \begin{cases} -B_1\,\dfrac{U_a^2}{2a^2k_a}\,[J_0(\dfrac{U_a r}{a}) - J_2(\dfrac{U_a r}{a})]Q & r<a \\ B_2\,\dfrac{W_a^2}{2a^2k_a}\,[K_0(\dfrac{W_a r}{a}) + K_2(\dfrac{W_a r}{a})]Q & r>a \end{cases} \qquad (21)$$

$$S_{\phi\phi} = \begin{cases} -B_1 \dfrac{U_a}{a\,k_a} [J_1 (\dfrac{U_a r}{a})/r]\, Q & r<a \\ -B_2 \dfrac{W_a}{a\,k_a} [K_1 (\dfrac{W_a r}{a})/r]\, Q & r>a \end{cases} \quad (22)$$

$$S_{zz} = \begin{cases} -B_1 k_a [J_0 (\dfrac{U_a r}{a})]\, Q & r<a \\ -B_2 k_a [K_0 (\dfrac{W_a r}{a})]\, Q & r>a \end{cases} \quad (23)$$

$$S_{rz} = \begin{cases} -B_1 \dfrac{U_a}{a} [J_1 (\dfrac{U_a r}{a})]\, Q & r<a \\ -B_2 \dfrac{W_a}{a} [K_1 (\dfrac{W_a r}{a})]\, Q & r>a \end{cases} \quad (24)$$

$$S_{\phi r} = S_{z\phi} = 0 \quad (25)$$

where B_1 and B_2 are the coefficients and $B_2 = B_1 J_0(U_a)/K_0(W_a)$; a subscript a denotes acoustic value; $Q=\exp[j(\omega t - k_a z]$; and r<a and r>a represent the fiber core and cladding regions respectively.

The coefficient B_1 can be determined from the view point of the acoustic power. The acoustic powers in the core and cladding are given by

$$P_{core} = p_0 t_{01} [J_0^2(U_a) + J_1^2(U_a)] \quad (26)$$

and

$$P_{clad} = -p_0 t_{02} [J_0(U_a)/K_0(W_a)]^2 [K_0^2(W_a) - K_1^2(W_a)] \quad (27)$$

where

$$p_0 = 2\pi\omega \bar{\mu}_a k_i a_a^2 |B_1|/2 \quad (28)$$

$$t_{0i} = (v_a^2/2v_{Si}^2) + (1-v_a^2/v_{Li}^2) \quad (29)$$

where i=1 and 2 represent r<a and r>a respectively and the Lame constant $\bar{\mu}_i$ is related to v_{Si} by

$$v_{Si} = \sqrt{\bar{\mu}_i/\rho_i} \quad (30)$$

In order to calculate the coupling coefficients given by Eq.(16), we consider normalized optical fields for HE_{11} mode. The electric fields of the HE_{11} mode is written as [17]

$$E_z = qf_1(r)\cos\phi \quad (31a)$$

$$E_r = -\frac{jKq}{U} f_0(r)\cos\phi \quad (31b)$$

$$E_\phi = -\frac{jKq}{U} f_0(r)\sin\theta \quad (31c)$$

where

$$K = \frac{V_o}{\sqrt{1 - (n_2^2/n_1^2)}} \quad (32)$$

and

$$f_n(r) = \begin{cases} J_n\left(\frac{U_o r}{a}\right) & r<a \quad (33a) \\ F_n K_n\left(\frac{W_o r}{a}\right), \quad \text{where } F_n = \frac{J_n(U_o)}{K_n(W_o)} & r>a \quad (33b) \end{cases}$$

The normalization factor q in Eq.(31) is given by

$$q = \left(\frac{\mu_0}{n_1^2}\right)^{1/4} \left(\frac{2}{\pi \xi_{0\,o}(W_o)}\right)^{1/2} \frac{U_o^2}{K V_o a J_{0\,o}(U_o)} \tag{34}$$

where μ_0 is the permeability of free space and $\xi_{0\,o}(W_o)$ is given by

$$\xi_{0\,o}(W_o) = K_{1\,o}^2(W_o)/K_{0\,o}(W_o). \tag{35}$$

Substituting the acoustic strains given by Eqs.(21)-(24), and the optical fields given by Eqs.(31)-(35) into Eq.(16), the coupling coefficient C^t is derived as

$$C^t = \frac{\omega_o \xi_0}{2\xi_{0\,o}(W_o)} \sqrt{\frac{\mu_0}{n_1^2}} \left(\frac{U_o^2}{aV_o J_{0\,o}(U_o)}\right)^2 (I_{rr}^t + I_{\phi\phi}^t + I_{zz}^t) \tag{36}$$

where

$$I_{rr}^t = n_1^4 (p_{11} + p_{22}) \frac{U_a^2}{2a^2 k_a} B_1 \int_0^a r\left[J_0\left(\frac{U_a r}{a}\right) - J_2\left(\frac{U_a r}{a}\right)\right] J_0^2\left(\frac{U_o r}{a}\right) dr$$

$$+ n_2^4 (p_{11} + p_{22}) \frac{-W_a^2}{2a^2 k_a} F_{0\,2} B \int_a^\infty r\left[K_0\left(\frac{W_a r}{a}\right) + K_2\left(\frac{W_a r}{a}\right)\right] K_0^2\left(\frac{W_o r}{a}\right) dr \tag{37a}$$

$$I_{\phi\phi}^t = n_1^4 (p_{11} + p_{22}) \frac{U_a}{a k_a} B_1 \int_0^a J_1\left(\frac{U_a r}{a}\right) J_0^2\left(\frac{U_o r}{a}\right) dr$$

$$+ n_2^4 (p_{11} + p_{22}) \frac{W_a}{a k_a} F_{0\,2} B \int_a^\infty K_1\left(\frac{W_a r}{a}\right) K_0^2\left(\frac{W_o r}{a}\right) dr \tag{37b}$$

$$I_{zz}^t = 2n_1^4 (p_{12}) k_a B_1 \int_0^a r J_0\left(\frac{U_a r}{a}\right) J_0^2\left(\frac{U_o r}{a}\right) dr$$

$$+ 2n_2^4 (p_{12})_2 k_a^2 F_{02}^2 B_2 \int_a^\infty rK_0\left(\frac{W_a r}{a}\right) K_0^2\left(\frac{W_o r}{a}\right) dr \qquad (37c)$$

and the coupling coefficient C_z is given by

$$C_z = \frac{\omega_o \varepsilon_0}{2\beta_0 (W_o)} \sqrt{\frac{\mu_0}{n_1^2}} \left(\frac{U_o^2}{KaV_o J_0(U_o)}\right)^2 (I_{rr}^z + I_{\phi\phi}^z + I_{zz}^z) \qquad (38)$$

where

$$I_{rr}^z = n_1^4 (p_{12})_1 \frac{U_a^2}{2a^2 k_a^2} B_1 \int_0^a r\left[J_0\left(\frac{U_a r}{a}\right) - J_2\left(\frac{U_a r}{a}\right)\right] J_1^2\left(\frac{U_o r}{a}\right) dr \qquad (39a)$$

$$+ n_2^4 (p_{12})_2 \frac{W_a^2}{2a^2 k_a^2} F_{12}^2 B_2 \int_a^\infty r\left[K_0\left(\frac{W_a r}{a}\right) + K_2\left(\frac{W_a r}{a}\right)\right] K_1^2\left(\frac{W_o r}{a}\right) dr$$

$$I_{\phi\phi}^z = n_1^4 (p_{12})_1 \frac{U_a}{a k_a^2} B_1 \int_0^a J_1\left(\frac{U_a r}{a}\right) J_1^2\left(\frac{U_o r}{a}\right) dr \qquad (39b)$$

$$+ n_2^4 (p_{12})_2 \frac{W_a}{a k_a^2} F_{12}^2 B_2 \int_a^\infty K_1\left(\frac{W_a r}{a}\right) K_1^2\left(\frac{W_o r}{a}\right) dr$$

$$I_{zz}^z = n_1^4 (p_{11})_1 k_a B_1 \int_0^a rJ_0\left(\frac{U_a r}{a}\right) J_1^2\left(\frac{U_o r}{a}\right) dr \qquad (39c)$$

$$+ n_2^4 (p_{11})_2 k_a^2 F_{12}^2 B_2 \int_a^\infty rK_0\left(\frac{W_a r}{a}\right) K_1^2\left(\frac{W_o r}{a}\right) dr$$

The photoelastic constants $(p_{ij})_1$ and $(p_{ij})_2$ denote the values in the core and cladding regions, respectively.

3.2c Numerical Calculation of the Coupling Coefficient

The coupling coefficient of the BCGWAO interaction in the fiber

discussed in section 3.2a are evaluated here. Consider the acoustic strains, given by Eqs.(21)-(24), with a total acoustic power of 1 watt. The field distribution of the strains is shown in Fig.4, where the densities in the core and cladding materials are assumed to be the same. Since the guided acoustic L_{01} mode in a weakly guiding fiber is close to a longitudinal plane wave [19], the component S_{zz} dominates. This strain has its maximum at the center of the core. The components S_{rr} and $S_{\phi\phi}$ are small enough to be neglected compared to S_{zz}. The strain S_{rr} has a discontinuity at the interface between the core and the cladding. The component S_{rz} is as small as one fifties of S_{zz} and is different in phase by $\pi/2$.

Coupling coefficient C is calculated as a function of V-value of acoustic waves, V_a, in Fig.5, where a constant v_{L1} value of 5933 m/s is assumed and the value v_{L2} is varied to change V_a. The photoelastic constants are assumed to be the value of vitreous silica at =0.6328 um as p_{11}=0.121, p_{12}=0.271 and p_{44}=-0.075 for the core and cladding materials [24]. In Fig.5, the components of the third term of Eq.(36) in the core and cladding regions are also plotted. The ratio of the coupling coefficient in the core to that in the cladding increases with the increase of V_a, because the acoustic power concentrates more in the core region with the increase of V_a. The contribution to the coupling coefficient from the other components, that is, the first and the second terms in Eq.(36) and the component C_z, is less than 0.5 percent. Therefore, the coupling coefficient is approximated by Eqs.(36) and (39), where I_{rr}^t and $I_{\phi\phi}^t$ are equal to zero.

The dependence of the coupling coefficient on the optical wavelength λ is calculated as shown in Fig.6(a), where the acoustic properties of the fiber are assumed to be v_{L1} =5933.0 m/s, v_{L2} =5943.0 m/s, v_{S1} =3764.0 m/s, v_{S2} =3770.3 m/s and ρ = 2.202x10^{3} kg/m^{3}. As the wavelength dispersion of refractive index in the fiber, the gradient $dn(\lambda)/d\lambda$ of a fused silica [25] was assumed for both core and cladding materials. The photoelastic constants were assumed to be independent of the wavelength. The acoustic frequency satisfying Eq.(2) is plotted as well as acoustic and optical V-values in Fig.6(b). The V-values in acoustic and optical waves are the same. The coupling coefficient C_t in the core increases with the decrease of the wavelength because both optical and acoustic power concentrate more in the core region. The total coupling coefficient also increases with the decrease of the wavelength. However, it is noted that the fiber becomes multimode when the V-value exceeds 2.405.

Now, consider the coupling efficiency using Eq.(14). The coupling coefficient C is 2.12x10^{4} m^{-1} when the acoustic power is equal to 1 watt. This coupling coefficient is proportional to a square root of acoustic power. Suppose the coupling length L be 100Λ, which corresponds to a total distance of 45.4 μm, where Λ is the acoustic wavelength. Then, the coupling efficiency is 55.6 % and 8.7 % when the acoustic power is 1 watt and 0.1 watt, respectively. If the coupling length can be 1000Λ, the coupling efficiency increases to 99.1 % and 55.6 % with acoustic power of 0.1 watt and 0.01 watt, respectively.

3.2d Wavelength Selectivity

As shown in Fig.5(b), the acoustic frequency required for the interaction depends on the optical wavelength λ. In this section, we will discuss the optical-wavelength selectivity. The wavelength dependence of the shift from the Bragg condition 2δ defined by Eq.(11) is written as

$$\frac{d(2\delta)}{d\lambda} \simeq -2\frac{dk_o}{d\lambda} = \frac{4\pi}{\lambda^2}\frac{dk_o}{dk_F} \tag{40}$$

where $k_F = 2\pi/\lambda$. The derivative dk_o/dk_F is represented by [17]

$$\frac{dk_o}{dk_F} \simeq N_2 + (N_1 - N_2)\frac{d(V_o b)}{dV_o} \tag{41}$$

where

$$N_i = n_i + k_F\frac{dn_i}{dk_F} \tag{42}$$

$$b \simeq 1 - (U_o/V_o)^2 \tag{43}$$

The wavelength selectivity $d\lambda/\lambda$ can be given using Eq.(40) as

$$\frac{d\lambda}{\lambda} = \frac{d(2\delta L)}{2\pi L\,(dk_o/dk_F)} \tag{44}$$

where Λ is the acoustic wavelength. The term $d(2\delta L)$ can be evaluated from Eq.(13). When $|C|L=\pi/2$, the width of $2\delta L$ for $\eta/\eta_0 > 0.5$ is $d(2\delta L) \simeq 5.0$.

Using the refractive index at $\lambda=1.31\ \mu m$, $N_1 - N_2 \simeq n_1 - n_2 = 0.0097$, and $N_2 = n_2 - dn_2/d\lambda = 1.4381$. Since $d(V_o b)/dV_o \simeq 1.15$ [17], dk_o/dk_F is calculated to be 1.4493. When $L=100\Lambda$, the wavelength selectivity $d\lambda/\lambda$ is evaluated to be 5.49×10^{-3}. Thus, the filtering bandwidth $d\lambda$ at $\lambda=1.31\ \mu m$ is found to be 72 Angstrons.

4. CONCLUSIONS AND DISCUSSIONS

The theoretical analysis for BCGWAO interactions in a weakly guiding single mode fiber was presented. This interaction is believed to be responsible for the experimental observation of backward Brillouin scattering phenomena reported in Ref.[9,11]. The coupling coefficient and optical filtering effect of BCGWAO interaction in a single mode fiber using the guided longitudinal L_{01} acoustic mode are given. As a result of recent progress on very high frequency piezoelectric transducers [13,14,26] which can be grown at the fiber end surface, in-line fiber-optic frequency shifters, tunable filters, switches, amplitude modulators, etc empolying BCGWAO interactions may be constructed.

If the BCGWAO interaction is taken place in a single mode fused silica optical fiber at λ=1.31 μm as described in Section 3.2a, the required acoustic frequency is around 13 GHz. If the interaction length is 100 acoustic wavelengths, the acoustic loss and the transit time across such length is about 9.5 dB and 7.6 ns respectively [27]. The insertion loss (one way) of the ultrasonic longitudinal transducer reported at this frequency was around 16 dB [13] and could be reduced [26]. Since efficient shear wave transducers at such high frequencies are also predicted theoretically [26], BCGWAO interactions with the lowest order guide shear (F_{11}) mode is currently under study. Future research will also include BCGWAO interactions in cladded single crystal fibers [28] which have much lower acoustic loss [27] and larger optical dispersion. The lower acoustic loss enhances the

effective BCGWAO interaction length thus the coupling efficiency, and the higher optical dispersion narrows the optical filter bandwidth.

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FIGURE CAPTIONS

Fig.1 A geometry of the device consisting of an ultrasonic transducer bonded to the termination of a cladded fiber in which guided acoustic and optical waves can propagate simultaneously with low loss and low dispersion.

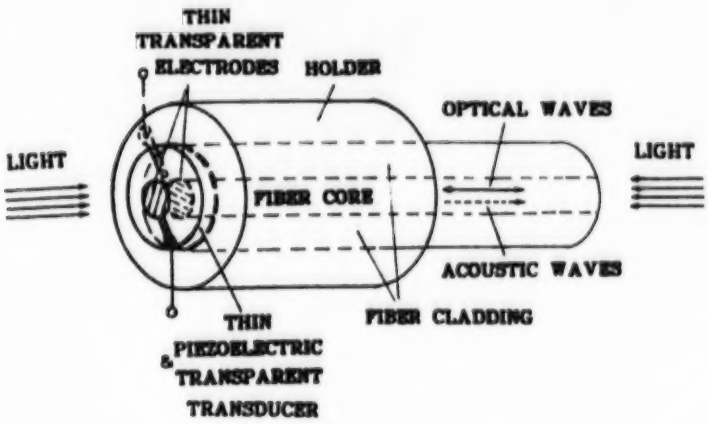
Fig.2 (a), (b) and (c) show three possible collinear acousto-optic interactions which may exist inside the fiber core of the cladded fiber in Fig.1. k_{oi} and k_{od} are two wavenumbers of the guided optical modes and k_a is that of the guided acoustic mode. Ω_o and f_a are the optical and acoustic frequency respectively.

Fig.3 The dispersion curves of a few lower order guided optical and acoustic modes in weakly guiding fibers. The guided modes are hybrid (HE_{nm} or EH_{nm}), transverse electrical (TE_{nm}) or transverse magnetic optical modes (TM_{nm}), and flexural or shear (F_{nm}), tortional (T_{nm}), radial-axial (R_{nm}) and longitudial (L_{nm}) modes; where n and m are the circumferential and azimuthal numbers respectively.

Fig.4 Strain distributions of L_{01} mode. The acoustic power is assumed to be 1 watt.

Fig.5 Coupling coefficient C as a function of V_a. Components $(C_t)_{zz}$, the third term of Eq.(36), in the core and cladding regions are also plotted.

Fig.6 (a) Dependence of the coupling coefficient on the optical wavelength, λ, and (b) the normalized acoustic ,V_a and optical, V_o, frequencies and the acoustic frequency, f, required for the BCGWAO interaction.



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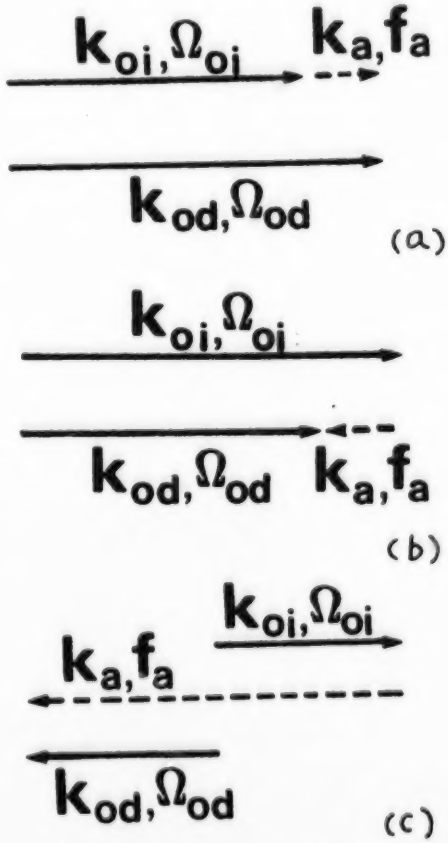

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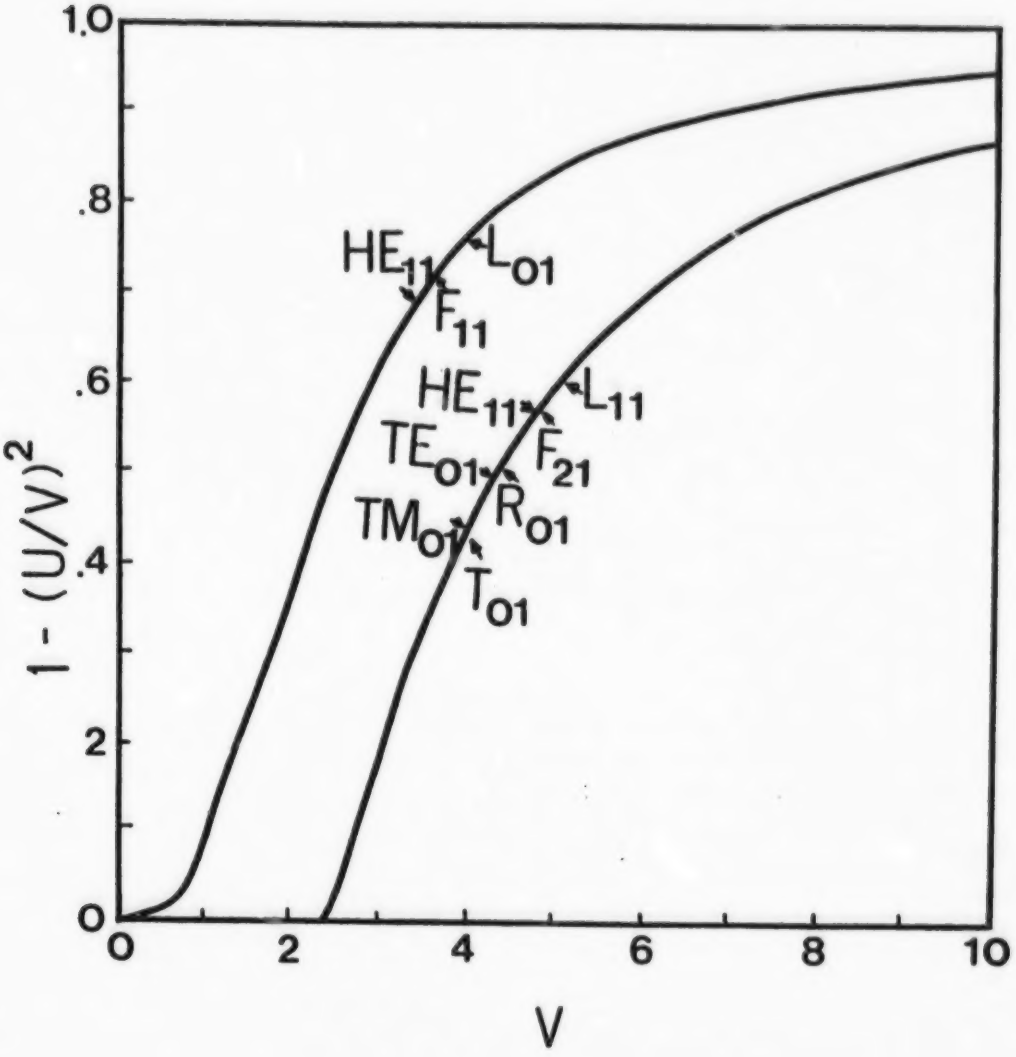

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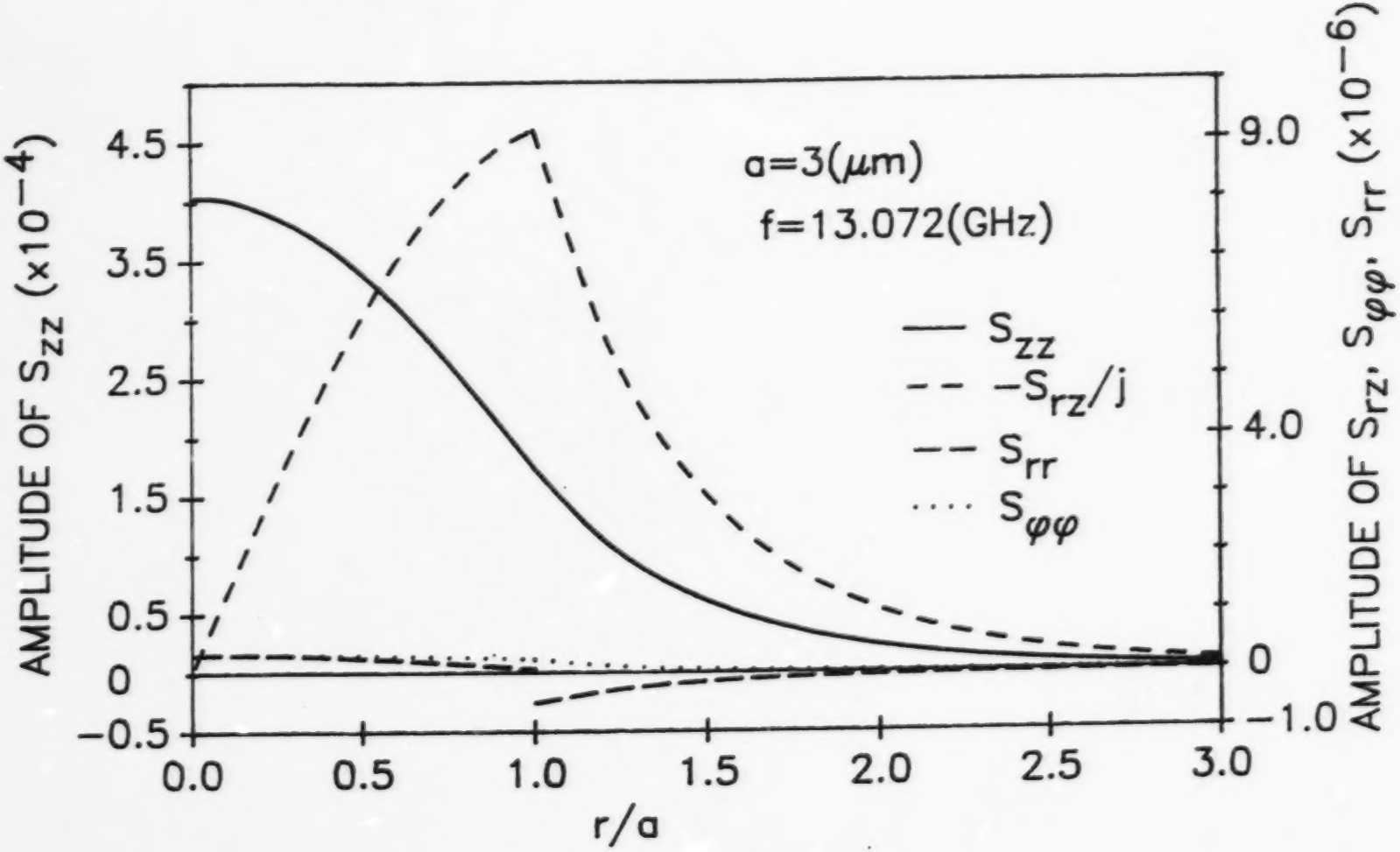

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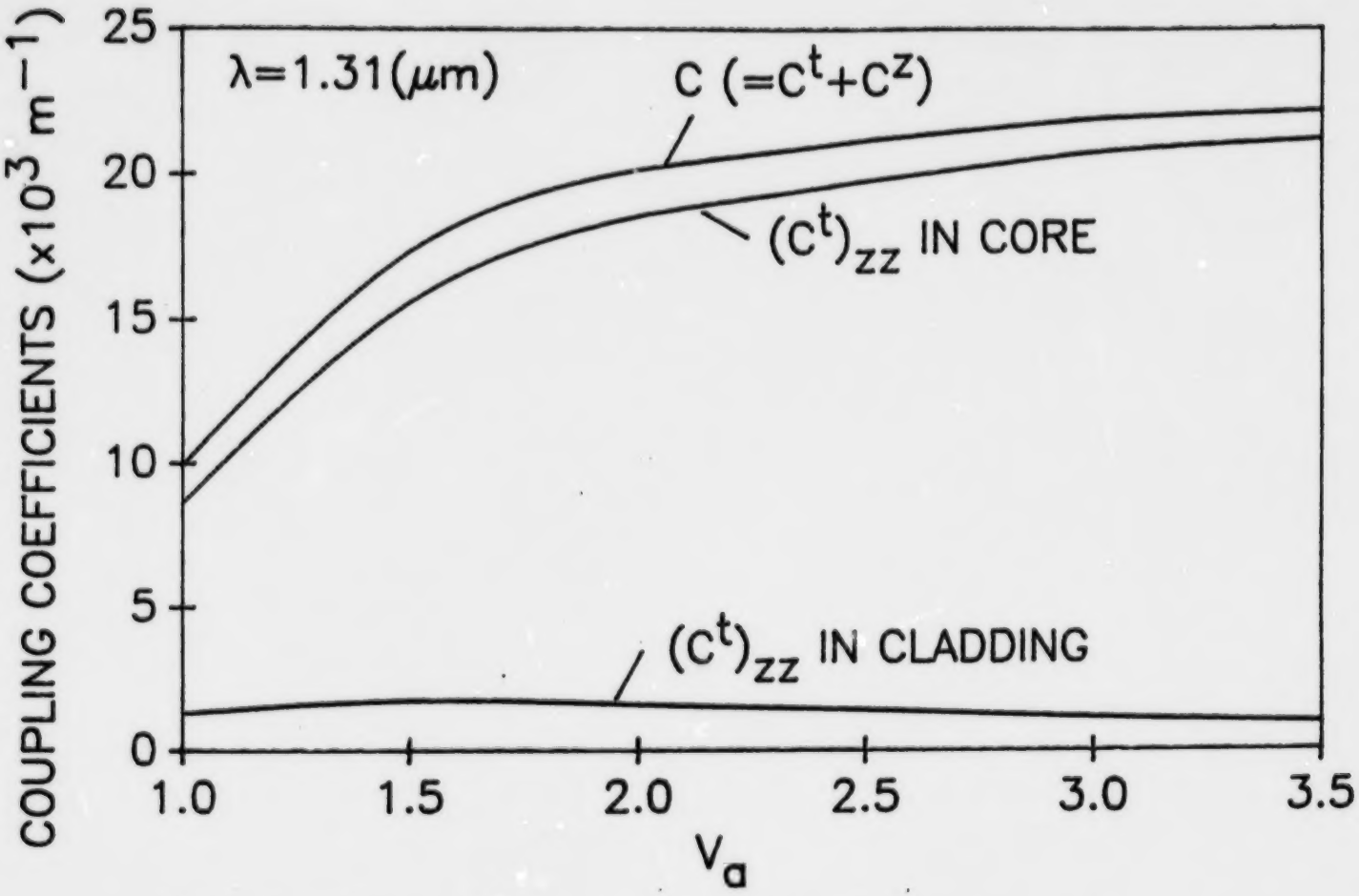

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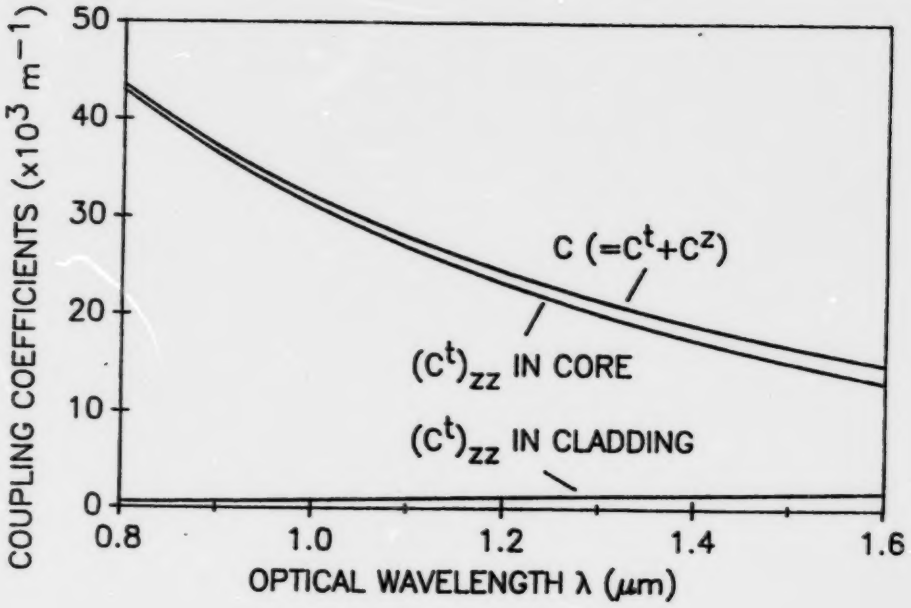
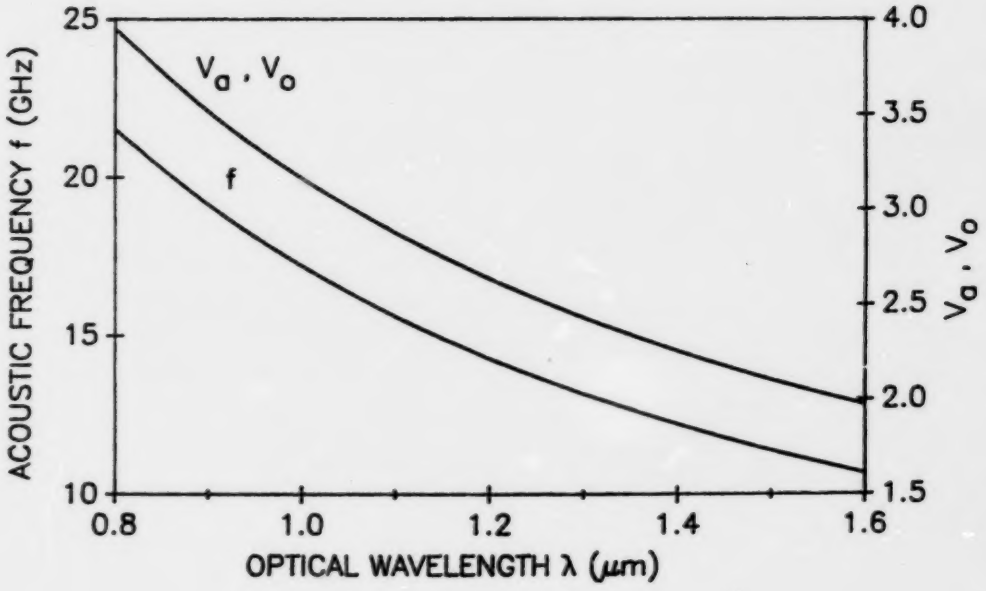


(a)



(b)

Fig.6 (a) Dependence of the coupling coefficient on the optical wavelength, λ, and (b) the normalized acoustic, V_a and optical, V_o, frequencies and the acoustic frequency, f, required for the BCGWAO interaction.